Introduction to Human Language Technologies
9. Syntactic parsing: parsers

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Outline

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Factors in parsing

Parsing performance depends on many aspects:

- Grammar expressivity (combination of symbols)
- Coverage (words)
- Parsing strategy (bottom-up, top-down)
- Rule application order (largest rule, most likely rule)
- Ambiguity management (keep all, select one - probabilities, semantics, pragmatics)
- ...

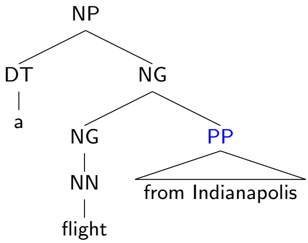
The problem of repeating derivations

- Top-down and bottom-up strategies both lead to repeated derivations when using backtracking

  Ex: "a flight from Indianapolis to Houston [on TWA...]"

  NG $\rightarrow$ NN

  NG $\rightarrow$ NG PP



The problem of repeating derivations

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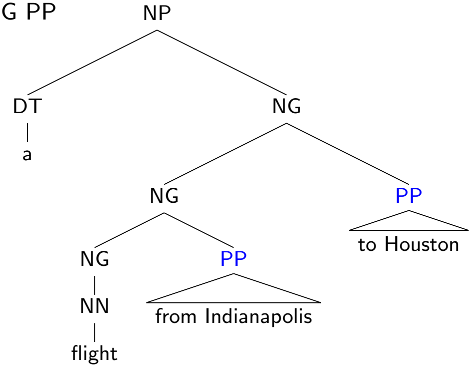
  Ex: "a flight from Indianapolis to Houston"

  NG → NN

  NG → NG PP



Outline

Properties

- They avoid re-doing derivations using dynamic programming.
- They represent derivations as a directed graph named chart.
- They use a dynamic programming table to build the chart.

Chart

- Nodes: positions between words of the input sentence
- Edges: dotted rules subsuming a sequence of words of the input sentence

- Dotted rules represent rules states:
  - Passive rules: $A \rightarrow B_1 \ldots B_k \bullet$
  - Active rules: $A \rightarrow B_1 \ldots B_i \bullet B_{i+1} \ldots B_k$

Ex:

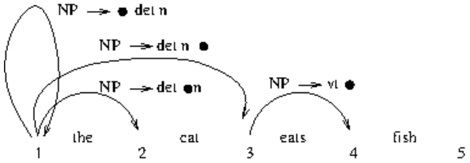
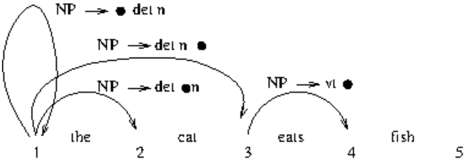


Chart as a dynamic programming table



				[1,5]
			[1,4]	[2,5]
		[1,3] NP $\rightarrow$ det n $\bullet$	[2,4]	[3,5]
	[1,2] NP $\rightarrow$ det $\bullet$ n	[2,3]	[3,4] VP $\rightarrow$ v_i $\bullet$	[4,5]
[1,1] NP $\rightarrow$ $\bullet$ det n	[2,2]	[3,3]	[4,4]	[5,5]
1	**2**	**3**	**4**	**5**

| the | cat | eats | fish |

Popular chart-based algorithms

- CKY algorithm (Younger, 1967)
  - introduced dynamic programming
  - limited to CFGs in Chomsky Normal Form
  - passive bottom-up chart parser (only passive rules)
  - straightforward probabilistic version
- Earley algorithm (Earley, 1970)
  - any CFG
  - active top-down parser (active/passive rules)
  - non-straightforward probabilistic version
- Generalized chart parsing (Kay, 1980)

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Chomsky Normal Form (CNF)

A CFG $G = (N, \Sigma, R, S)$ expressed in CNF is as follows:

- N is a set of non-terminal symbols
- Σ is a set of terminal symbols
- R is a set of rules which take one of two forms:
  - $X \rightarrow Y_1 Y_2$ for $X, Y_1, Y_2 \in N$
  - $X \rightarrow \alpha$ for $X \in N$ and $\alpha \in \Sigma$
- $S \in N$ is a start symbol

Any CFG can be converted into CNF

CNF conversion

1. Convert Hybrid rules: replace terminals with new non-terminals

   Ex: $INF\_VP \rightarrow to\ VP \Longrightarrow$
   $INF\_VP \rightarrow TO\ VP$
   $TO \rightarrow to$

2. Convert non-binary rules:

   Ex: $S \rightarrow VP\ NP\ PP \Longrightarrow$
   $S \rightarrow VP\ X$
   $X \rightarrow NP\ PP$

3. Convert unit productions: $A \rightarrow^* B$ and $B \rightarrow \alpha \Longrightarrow A \rightarrow \alpha$

   Ex: $NP \rightarrow N$ and $N \rightarrow dog \Longrightarrow NP \rightarrow dog$

Exercise

Convert the following CFG to CNF

1. $S \rightarrow NP\ VP$
2. $NP \rightarrow det\ n$
3. $NP \rightarrow n$
4. $VP \rightarrow vt\ NP\ PP$
5. $VP \rightarrow vi$
6. $PP \rightarrow with\ NP$
7. $det \rightarrow the|a$
8. $n \rightarrow cat|fish|knife$
9. $vt \rightarrow eats$
10. $vi \rightarrow eats$

CKY Algorithm

Chart content:

- Maximum probability of a subtree with root X spanning words $i \ldots j$:

$$\pi(i, j, X)$$

- Backpath to recover which rules produced the maximum probability tree:

$$\psi(i, j, X)$$

The goal is to compute:

- $\max_{t \in \mathcal{T}(s)} p(t) = \pi(1, n, S)$
- $\psi(1, n, S)$
- It is possible to use it without probabilities to get all parse trees (with higher complexity)

CKY Algorithm

Base case: Tree leaves

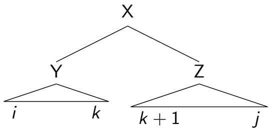
- $\forall i = 1 \ldots n, \forall X \rightarrow w_i \in R, \quad \pi(i, i, X) = q(X \rightarrow w_i)$

Recursive case: Non-terminal nodes

- $\forall i = 1 \ldots n, \forall j = (i+1) \ldots n, \forall X \in N$

$$\pi(i, j, X) = \max_{\substack{X \rightarrow YZ \in R \\ k : i \leq k < j}} q(X \rightarrow YZ) \times \pi(i, k, Y) \times \pi(k+1, j, Z)$$

$$\psi(i, j, X) = \arg \max_{\substack{X \rightarrow YZ \in R \\ k : i \leq k < j}} q(X \rightarrow YZ) \times \pi(i, k, Y) \times \pi(k+1, j, Z)$$



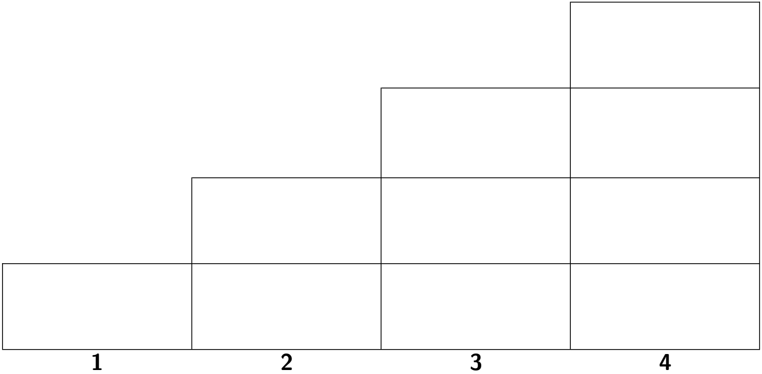
Output:

- Return $\pi(1, n, S)$ and recover backpath through $\psi(1, n, S)$

CKY Algorithm

Supose $s = w_1 w_2 w_3 w_4$ and $G =< N, \Sigma, S, R, q >$ a PCFG

$R = \{X_k \to Y_s Z_t\} \cup \{X_k \to \alpha\}$



CKY Algorithm

Supose $s = w_1 w_2 w_3 w_4$ and $G =< N, \Sigma, S, R, q >$ a PCFG

$R = \{X_k \to Y_s\, Z_t\} \cup \{X_k \to \alpha\}$

Base case:

$\forall_k$ shot $\{X_k \to w_i\}$ to compute $\pi(i, i, X_k)$

11 $\{X_k \to w_1\}_k$	22 $\{X_k \to w_2\}_k$	33 $\{X_k \to w_3\}_k$	44 $\{X_k \to w_4\}_k$
1	**2**	**3**	**4**

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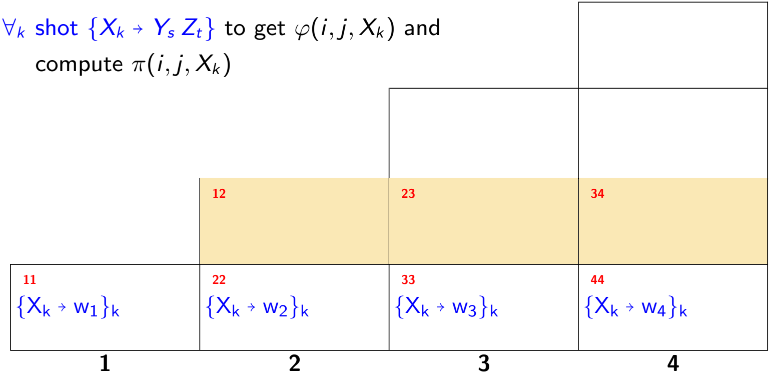
Recursive case:

$\forall_k$ shot $\{X_k \rightarrow Y_s\, Z_t\}$ to get $\varphi(i, j, X_k)$ and compute $\pi(i, j, X_k)$



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Recursive case:

$\forall_k$ shot $\{X_k \to Y_s\, Z_t\}$ to get $\varphi(i, j, X_k)$ and compute $\pi(i, j, X_k)$

		13	24
	12	23	34
11 $\{X_k \to w_1\}_k$	22 $\{X_k \to w_2\}_k$	33 $\{X_k \to w_3\}_k$	44 $\{X_k \to w_4\}_k$
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			14
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$\forall_k$ shot $\{X_k \rightarrow Y_s\, Z_t\}$ to get $\varphi(i, j, X_k)$ and compute $\pi(i, j, X_k)$

Example for (1,3)

		13 $\{X_k \rightarrow Y_{s,11}\, Z_{t,23}\}_k$	24
	12	23	34
11 $\{X_k \rightarrow w_1\}_k$	22 $\{X_k \rightarrow w_2\}_k$	33 $\{X_k \rightarrow w_3\}_k$	44 $\{X_k \rightarrow w_4\}_k$
1	**2**	**3**	**4**

CKY Algorithm

Supose $s = w_1 w_2 w_3 w_4$ and $G =< N, \Sigma, S, R, q >$ a PCFG

$R = \{X_k \rightarrow Y_s\, Z_t\} \cup \{X_k \rightarrow \alpha\}$

Recursive case:

$\forall_k$ shot $\{X_k \rightarrow Y_s\, Z_t\}$ to get $\varphi(i, j, X_k)$ and compute $\pi(i, j, X_k)$

Example for (1,3)		13 $\{X_k \rightarrow Y_{s,12}\, Z_{t,33}\}_k$	24
	12	23	34
11 $\{X_k \rightarrow w_1\}_k$	22 $\{X_k \rightarrow w_2\}_k$	33 $\{X_k \rightarrow w_3\}_k$	44 $\{X_k \rightarrow w_4\}_k$
1	**2**	**3**	**4**

CKY Algorithm

Input: a sentence $s = x_1 \ldots x_n$, a PCFG $G = (N, \Sigma, S, R, q)$.
Initialization:
For all $i \in \{1 \ldots n\}$, for all $X \in N$,

$$\pi(i, i, X) = \begin{cases} q(X \rightarrow x_i) & \text{if } X \rightarrow x_i \in R \\ 0 & \text{otherwise} \end{cases}$$

Algorithm:

- For $l = 1 \ldots (n-1)$
  - For $i = 1 \ldots (n-l)$
    - Set $j = i + l$
    - For all $X \in N$, calculate

$$\pi(i, j, X) = \max_{\substack{X \rightarrow Y Z \in R, \\ s \in \{i \ldots (j-1)\}}} (q(X \rightarrow Y Z) \times \pi(i, s, Y) \times \pi(s+1, j, Z))$$

and

$$bp(i, j, X) = \arg \max_{\substack{X \rightarrow Y Z \in R, \\ s \in \{i \ldots (j-1)\}}} (q(X \rightarrow Y Z) \times \pi(i, s, Y) \times \pi(s+1, j, Z))$$

Output: Return $\pi(1, n, S) = \max_{t \in \mathcal{T}(s)} p(t)$, and backpointers bp which allow recovery of $\arg\max_{t \in \mathcal{T}(s)} p(t)$.

Exercise

Compute the best parse tree and its probability for the following input sentence using the PCFG:

"the woman saw the man with the telescope"

S → NP VP	0.5	Vi → sleeps	1.0
S → NP Vi	0.5	Vt → saw	1.0
NP → DT NN	0.4	NN → man	0.7
NP → NP PP	0.6	NN → woman	0.2
PP → IN NP	1.0	NN → telescope	0.1
VP → Vt NP	0.4	DT → the	1.0
VP → VP PP	0.1	IN → with	0.5
VP → Vi PP	0.5	IN → in	0.5